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An approximate but efficient technique is presented that accounts for vertical polarization and rough surface effects over the sea for ducting conditions using the split-step parabolic equation method. The primary justification for this semi-empirical technique is that in most cases propagation loss predictions match results from a waveguide model that is believed to account for these effects properly. The technique and comparisons of modeled results versus waveguide results and measured data are examined.

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Modeling Surface Effects with the Parabolic Equation Method

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ABSTRACT

An approximate but efficient technique is presented that accounts for vertical polarization and rough surface effects over the sea for ducting conditions using the split-step parabolic equation method. The primary justification for this semi-empirical technique is that in most cases propagation loss predictions match results from a waveguide model that is believed to account for these effects properly. The technique and comparisons of modeled results versus waveguide results and measured data are examined.

INTRODUCTION

The split-step parabolic equation (PE) method has proven to be an accurate and efficient radio propagation model for conditions in which the vertical refractive-index profile changes along the path of propagation (Dockery, 1988; Craig, 1989; Barrios, 1992). The simplest and most efficient PE models are based on sine fast Fourier transforms (FFTs) that assume perfect reflection from the lower boundary. This assumption is very good for horizontal polarization over a smooth sea where reflection at all grazing angles is nearly perfect, but it is in error for vertical polarization and rough surface cases, since reflection from the sea in these cases is not perfect. This paper presents an efficient, semi-empirical method to include vertical polarization and rough surface effects in PE models that use sine FFTs. This approximate method is desired for incorporation into the Radio Physical Optics (RPO) propagation model (Hitney, 1992), which is a hybrid model that combines both ray-optics and PE methods for maximum efficiency. As currently configured, RPO includes the effects of vertical polarization and surface roughness in the ray-optics portions of the model used for elevation angles above approximately 1 degree, but not in the PE part of the model used for lower elevation angles.

In this paper a waveguide program (Baumgartner, 1983; Baumgartner et al., 1983; Hitney, et. al., 1985), now known as MLAYER (for multilayer, since it accepts multiple levels in the refractivity profile), has been selected as a standard or "ground truth" model. Although MLAYER only models horizontally homogeneous refractivity profiles, it does treat the effects of nonperfect reflection from the lower boundary in a theoretically rigorous manner based on the Fresnel reflection coefficient modified for surface roughness by the Miller-Brown (1984) model. This model is given by

$$R = R_0 \exp\left[-2(2\pi g)^2\right] I_0\left[2(2\pi g)^2\right] \qquad (1)$$

where R is the rough-surface coherent reflection coefficient, R_0 is the ordinary Fresnel reflection coefficient, I_0 is the modified Bessel function, and the "apparent ocean roughness" g is given by

$$g = (\sigma_h \sin\psi)/\lambda \qquad (2)$$

where σ_h is the standard deviation of the sea-surface elevation, ψ is the grazing angle, and λ is the electromagnetic wavelength. The relationship of σ_h to wind speed is derived from the Phillips' saturation curve spectrum (Phillips, 1966) and is given by

$$\sigma_h = 0.0051\, u^2 \qquad (3)$$

where u is wind speed in meters per second.

Comparisons of RPO (without modification) and MLAYER results show excellent agreement to within 0.1 dB for homogeneous surface ducting cases for horizontal polarization and smooth sea conditions (Hitney, 1992). A surface duct is considered to be any duct where the modified refractivity M at some height above the sea surface is less than M at the sea surface. $M = (n - 1 + z/a)\, 10^6$, where n is the refractive index, z is height, and a is the earth radius. These ducts include both surface-based ducts from elevated trapping layers and evaporation ducts. Other comparisons for non-surface-ducting conditions also show excellent agreement for both perfect and non-perfect reflection from the sea. The only substantial disagreements found between the two models are for cases of surface ducting and nonperfect reflection from the sea. In these cases, there is a strong interaction between the ducting and reflecting mechanisms; therefore, multiple nonperfect reflections from the sea appear to be a substantial factor in propagation.

Figure 1 shows an example of the disagreement between RPO and MLAYER for a 24 m evaporation duct for a wind speed of 20 m/s. The modified refractivity profile for this duct is given in Table 1. The frequency is 3 GHz, polarization is horizontal, and the transmitter and receiver heights are 25 meters above sea level. Figure 1 shows propagation loss versus range from RPO and MLAYER, plus reference values for free-space loss and standard atmosphere loss

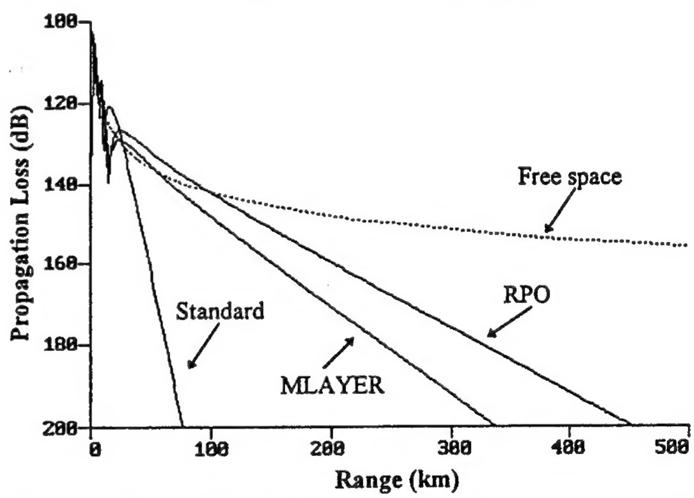

Figure 1. RPO and MLAYER results for a 24-meter evaporation duct, plus free space and standard conditions for reference. Frequency is 3 GHz, transmitter and receiver heights are 25 m.

TABLE 1. *Profile of modified refractivity (M) versus height for the 24-meter evaporation duct environment of Figure 1.*

Height (m)	*M*-units	Height (m)	*M*-units
0.00	350.00	7.39	318.51
0.14	329.60	12.18	317.61
0.22	328.11	20.09	317.10
0.37	326.63	24.00	317.05
0.61	325.16	33.12	317.22
1.00	323.71	54.60	318.41
1.65	322.29	90.02	321.34
2.72	320.92	148.41	327.14
4.48	319.65		

from RPO. Both models show substantial reductions in loss (increases in signal strength) compared to the standard case, but only MLAYER accounts for the surface roughness effects. The difference between the two models can be substantial, for example about 16 dB at a range of 300 km. Based on these and similar model comparisons, it seemed possible that a semi-empirical method to adjust the PE model might be developed from a sufficient number of MLAYER cases for nonperfect reflection under surface ducting conditions.

MODEL DEVELOPMENT

The sine-FFT PE model in RPO can be modified to match many MLAYER cases by multiplying the magnitude of the lowest field point in the PE model by a boundary loss factor (B) between zero and one immediately before each PE range step calculation. Figures 2 and 3 illustrate this concept at 9 GHz for the same 24 m evaporation duct modeled in Figure 1. Figures 2 and 3 show propagation loss versus receiver height from 0 to 100 m at a range of 500 km for four cases: horizontal polarization and a smooth sea; vertical polarization and a smooth sea; vertical polarization and 10 m/s of wind; and vertical polarization and 20 m/s of wind. Figure 2 shows results from MLAYER, while Figure 3 shows results from RPO applying the B values indicated. It is apparent from these two figures that an appropriate boundary loss factor can be found that will simulate vertical polarization and various surface roughness effects for this environment. Many other surface-duct environments have been tried with comparable results.

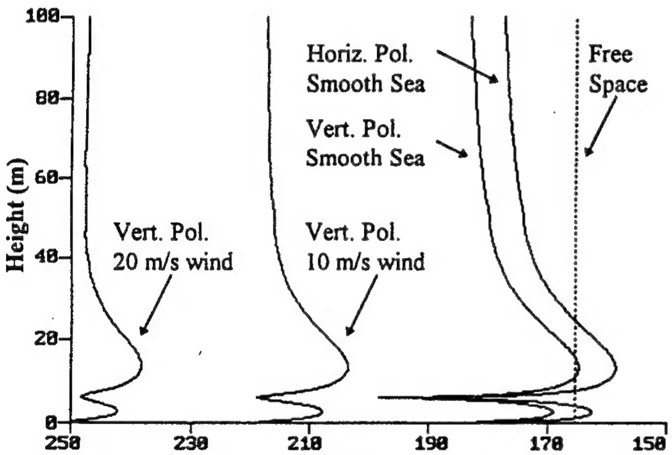

Figure 2. MLAYER results for a 24-m evaporation duct. Frequency is 9 GHz, transmitter height is 25 m, and range is 500 km.

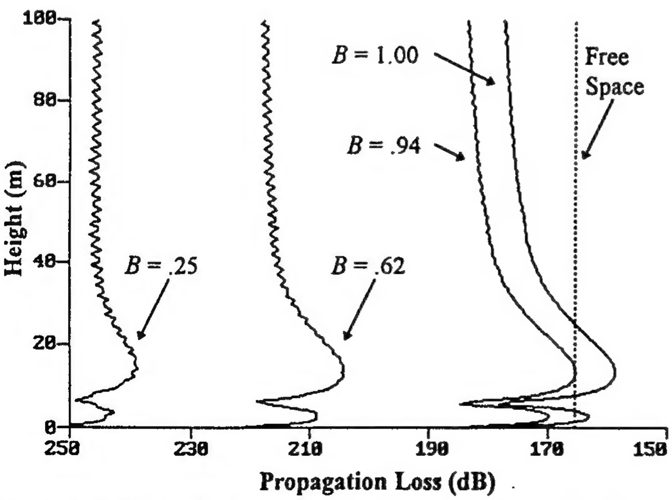

Figure 3. RPO results for various boundary loss factors (B) for the same conditions as Figure 2.

TABLE 2. *Boundary loss factors (B) for RPO that best match the results from MLAYER for 14 conditions. a: 24 m evaporation duct, b: 300 m surface-based duct, c: 46 m surface duct.*

Profile	Freq. (GHz)	Wind (m/s)	B
a	3.0	0.	0.91
a	3.0	10.	0.85
a	3.0	20.	0.49
a	9.0	0.	0.94
a	9.0	10.	0.62
a	9.0	20.	0.25
b	0.1	0.	0.50
b	0.3	0.	0.78
b	3.0	0.	0.92
b	3.0	10.	0.86
b	3.0	20.	0.40
c	10.0	0.	0.94
c	10.0	10.	0.64
c	10.0	20.	0.10

TABLE 3.
300 m surface-based duct

Height (m)	*M*-units
0.0	339.0
250.0	368.5
300.0	319.0
1000.0	401.6

TABLE 4.
46 m surface duct

Height (m)	*M*-units
0.0	350.0
45.7	334.7
1524.0	506.7

Table 2 lists 14 conditions and the corresponding RPO boundary loss factors that best matched the results from MLAYER. A total of three environmental conditions were used, consisting of: (a) the 24 m evaporation duct already described; (b) a 300 m thick surface-based duct from an elevated trapping layer described by Table 3; and (c) a 46 m thick surface duct described by Table 4. In all cases the transmitter height was 25 m and vertical polarization was assumed. The ranges varied between 200 and 500 km and the best fit boundary loss factors were determined by visual examination of plots of propagation loss versus height in the lowest 100 m.

The results of Table 2 were used to develop a function from which the boundary loss factor B could be computed based on parameters of the refractivity profile and the PE range step. Experiments with the PE model using various combinations of B values and range steps consistently showed an exponential relationship between B and the PE range step. For example, results obtained with $B = 0.5$ and a 500 m range step were equal to results obtained with $B = 0.25$ and a 1000 m range step. Other numerical experiments indicated a strong relationship between B and the reflection coefficient for the maximum grazing angle that could be trapped by the surface duct. A somewhat weaker relationship was also found between B and the distance between successive reflections of the ray defined by the maximum grazing angle that could be trapped, hereafter referred to as the "skip distance." Combining the above considerations led to the semi-empirical relationship for boundary loss factor B given by

$$B = |R(\psi)|^{131\,\delta x / x_s} \tag{4}$$

where R is the Fresnel reflection coefficient from (1), ψ is the maximum grazing angle that can be trapped by the surface duct, δx is the PE range step, and x_s is the skip distance of a ray with grazing angle ψ in the duct. The coefficient 131 was determined by an iterative process to best match the B values given in Table 2. The maximum grazing angle is computed from ray optics theory using

$$\psi = \sqrt{2 \times 10^{-6}(M_0 - M_m)} \tag{5}$$

where M_0 is the modified refractivity at the surface and M_m is the minimum modified refractivity on the profile. The skip distance is computed using a simple ray trace procedure on each linear modified refractivity segment of the profile. Figure 4 shows a scatter plot of the boundary loss factors from Table 2 and determined from (4). A perfect fit would show all points on the dashed diagonal line.

The one point furthest from the dashed line in Figure 4 corresponds to the 46 m surface duct environment for a 10 m/s wind speed. From a waveguide theory point of view, this case is characterized by many trapped modes for which the eigenangles are spread over a substantial angular interval. In this case, the computed value of B is unrealistic, since (4) assumes that the reflection coefficient depends on only one grazing angle. In this case, $R = 0.51$. However, the other two cases, using the same duct environment and characterized by $R = 0.92$ and $R = 0.11$ in (4), did fit well in Figure 4. This effect implies that (4) is most likely to be in error for mid-range reflection coefficients typical of moderate sea roughness.

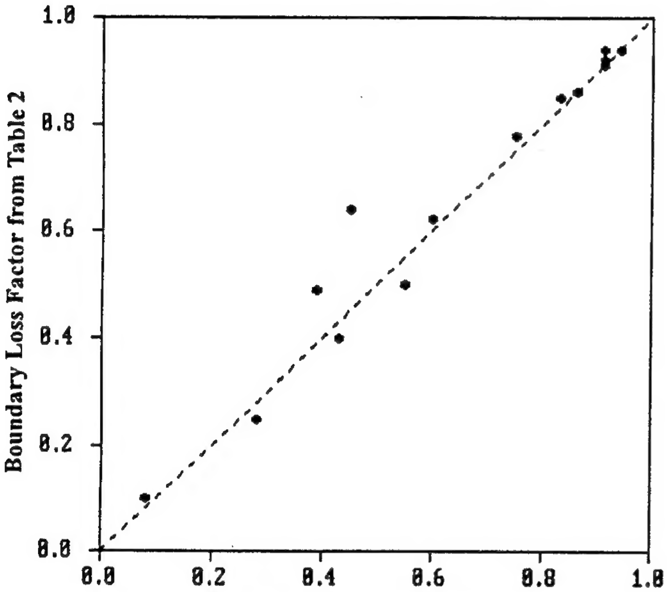

Figure 4. Scatter plot of boundary loss factors computed by (4) and the best fit to MLAYER results from Table 2.

INDEPENDENT TEST

To test the boundary loss factor described by (4) and its use in the PE model, it is desirable to select a test case that is independent from those cases summarized in Table 2. In 1972, a multifrequency radio propagation experiment was conducted in the Aegean Sea between the islands of Mykonos and Naxos, Greece (Richter and Hitney, 1988). Since surface roughness effects should be greater at higher frequencies, we will consider here only the highest frequency of 37.4 GHz used in this experiment. The path length was 35.2 km, the transmitter height was 5.1 m above mean sea level, and horizontal polarization was used.

Figure 5 shows propagation loss versus height from 0 to 50 m for a typical evaporation duct of 12 m duct height and an assumed wind speed of 10 m/s. The figure shows results from RPO with the modification described here, RPO without any modification, and the results from MLAYER. The results from RPO, with the modification, are in substantial agreement with MLAYER, and are very different from the unmodified RPO results. Two receiver heights at 3.6 and 8.6 m above mean sea level were used in this experiment at 37.4 GHz. Figure 5 shows that the lower receiver in this case would experience about 20 dB of extra loss from surface roughness compared to the smooth surface case assumed by the unmodified RPO results. For the higher receiver, both results are about equal for this geometry.

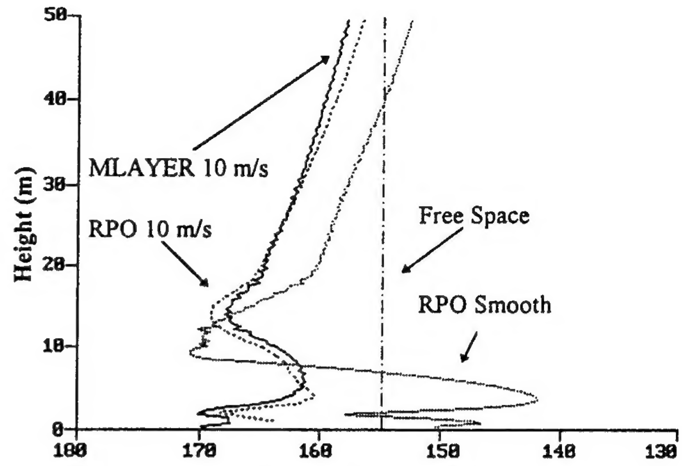

Figure 5. Comparison of RPO and MLAYER models for a 12 m evaporation duct at 37.4 GHz. Polarization is horizontal, the transmitter height is 5.1 m, and the range is 35.2 km.

Figure 6 compares modeled and observed propagation loss for the lower receiver versus time for the period from 7 to 22 November, 1972. The upper panel shows RPO without the surface roughness model and the lower panel shows RPO with the surface roughness model. Both panels show modeled results as solid lines and observed loss data as points each 15 minutes, except for a few periods when the equipment was not operating. Reference lines are also included for free space and standard-atmosphere diffraction propagation loss levels. The models were driven with hourly bulk observations of surface air temperature, humidity, and wind speed plus sea temperature recorded at Mykonos. For each hourly observation, an evaporation duct height and associated modified refractivity versus height profile was generated (Paulus, 1985) for input to the RPO model. The roughness model also used the hourly measured wind speed. The RPO model does not include effects of gaseous absorption, which would add approximately 5 dB of loss to the modeled results in Figure 6. In spite of this shortcoming, it is quite obvious from the figure that the roughness model described here is an improvement to the RPO PE model. Improvements of up to 25 dB are most pronounced from 7 to 11 November when the wind speeds were at relatively high values of up to 10 m/s.

The approximate method is quite efficient in terms of source code and increased execution time. As implemented in RPO, the method adds less than 25 lines of source code to a base of about 1100 lines. The execution time in all cases tried is only very slightly increased, with normal increases being much less than one percent. The method could also be easily extended to range-dependent environments by evaluating (4) at each range step as the environmental conditions change along the propagation path, however this has not yet been tried.

CONCLUSIONS

The method presented here appears to be a reasonably accurate and very efficient method to account for nonperfect reflections from the sea surface in split-step, sine-FFT parabolic equation models such as the model used in RPO. However, the method should still be tested on a wider variety of environmental conditions before it is widely accepted. Also, the method should be implemented and evaluated for conditions where either the ducting environment or the surface-roughness change along the propagation path.

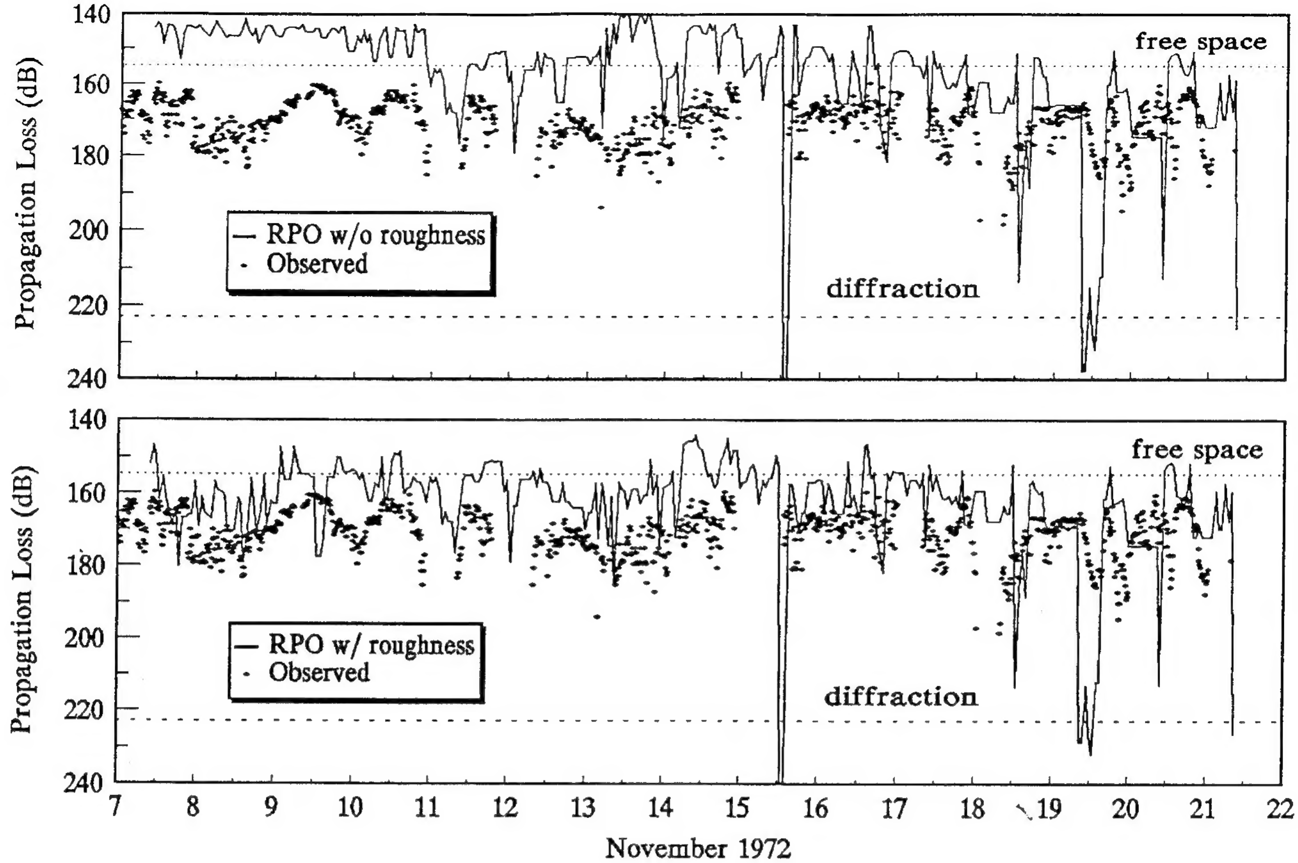

Figure 6. RPO results with and without the roughness model compared to observations for horizontal polarization at 37.4 GHz. Transmitter and receiver antennas were 5.1 and 3.6 meters above mean sea level, respectively.

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REFERENCES

Barrios, A.E. "Parabolic equation modeling in horizontally inhomogeneous environments." *IEEE Trans. Antennas Propagat.*, 40 (1992): pp. 791-797.

Baumgartner, G.B. Jr. "XWVG: a waveguide program for trilinear tropospheric ducts." Naval Ocean Systems Center Tech. Doc. 610, 1983, 206 pp.

Baumgartner, G.B. Jr., H.V. Hitney, and R.A. Pappert. "Duct propagation modelling for the integrated-refractive-effects prediction system (IREPS)." *IEE Proceedings Part F*, 130 (1983): pp. 630-642.

Craig, K.H. "Propagation modeling in the troposphere: parabolic equation method." *Electron. Lett.*, 24 (1989): pp. 1136-1139.

Dockery, G.D. "Modeling electromagnetic wave propagation in the troposphere using the parabolic equation." *IEEE Trans. Antennas Propagat.*, 36 (1988): pp. 1464-1470.

Hitney, H.V. "Hybrid ray optics and parabolic equation methods for radar propagation modeling," in Radar 92, IEE Conference Proceedings No. 365, 1992, pp. 58-61.

Hitney, H.V., J.H. Richter, R.A. Pappert, K.D. Anderson, and G.B. Baumgartner, Jr. "Tropospheric radio propagation assessment." *Proc. IEEE*, 73 (1985): pp. 265-283.

Miller, A.R., R.M. Brown, and E. Vegh. "New derivation for the rough-surface reflection coefficient and for the distribution of sea-wave elevations." *IEE Proceedings Part F*, 131 (1984): pp. 114-116.

Paulus, R.A. "Practical application of an evaporation duct model." *Radio Sci.*, 20 (1985): pp. 887-896.

Phillips, O.M. *Dynamics of the Upper Ocean*, London: Cambridge University Press, 1966.

Richter, J.H. and H.V. Hitney. "Antenna heights for the optimum utilization of the oceanic evaporation duct, part III: results from the Mediterranean measurements." Naval Ocean Systems Center Tech. Doc. 1209, Vol. 2, 1988, 283 pp.